Research on laser photoelectric detection performance and SNR model of space target in laser detection system

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To enhance and improve the space target detection performance of laser photoelectric detection system in sea level, this paper established the space target characteristics calculation models and signal-to-noise ratio (*SNR*) model according to the laser detection principle on sea surface, and deduced their calculation function and gave appropriate calculation analysis; researched space target radiation characteristics and derived the total photosensitive surface luminance function in photoelectric detector; analyzed the effect factors on *SNR* in different background luminance. Spectral filtering method was applied to weaken strong luminance influence, and detection distance calculation function was set up based on *SNR* and the contrast. Through the calculation and experiment analysis, the results showed the calculation models of photoelectric detection performance and *SNR* were correct and scientific, and the suitable spectral filtering technique could effectively improve *SNR*.

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1. Introduction

Photoelectric detection technology is widely applied in aviation, spaceflight, colliery, industrial buildings and traffic fields, especially the infrared photoelectric detection technology. The infrared photoelectric detection technology adopts single-wavelength detecting principle and has better detecting stability [1-3]. However, because of the complexity of sea surface environment, laser detection system is affected by different stray lights, especially the reflected sunlight by the waves on sea surface, the reflection and scattering of space target [4-5], which leads the features of target in detection system to be unobvious and reduces the target detection performance. How to effectively enhance the detection performance of photoelectric detection system is one of the key techniques, which is the linchpin for improving combat capability of maritime weapon system [6]. For detection methods on space target, many experts researched target features under visible light irradiation and established detection models, for instance, the detection performance model based on bidirectional reflectance distribution function (*BRD*F) in [7]. These experts researched space reflectance distribution characteristics and spectral characteristics for different materials targets. [8-9] analyzed the characteristics of targets in photoelectric detection system in daytime and constructed 3D model of Iridium Satellite via MATLAB. Current literatures had few researches on large visual field photoelectric detection performance，and did not build perfect computing models and analysis methods for space target of photoelectric detection performance. In addition, because of the diversity and particularity of targets, such as the size, shape, reflective material, speed, etc., the calculations of detection capabilities on space dynamic target are more complex. This paper, based on the principle of the laser target detection, researches the calculation methods of detection performance in photoelectric detection system according to target characteristics, luminance and responsivity of photoelectric detector etc.

2. The detection principle of space target in laser detection system

Fig. 1 is detection principle of space target in laser detection system. Laser detection system is composed of two parts which are laser emission part and laser receiving detection part [10]. The effective detection field is a confluence area, which is structured via the visual field of emitting laser and the visual field of receiving detection. The visual field of emitting laser depends on the laser emitting angle and the visual field of receiving detection depends on the photosensitive surface of photoelectric detector. Modulated laser is adopted to accomplish laser emission task. In order to effectively improve detection distance, the width value of laser pulse should be as narrow as possible and the value of laser emission frequency should be as high as possible, which is propitious to detect the reflective energy during high-speed target passing through the laser effective detection field. The laser receiving detection part mainly adopts photoelectric detector with high responsivity and low noise. The photoelectric detector has characteristic of high response to single band laser. This paper uses the value of reflective energy to ascertain detection performance on space target in sea level [11], and the reflective energy is from target surface during the target passing through the laser effective detection field. In order to effectively establish detection performance model on space target in sea level, this paper mainly analyzes the *SNR* and detection distance of the laser photoelectric detection system. Therefore, it needs to research the target characteristics in laser detection field, background luminance and the functional relation between the reflective energy on space target and the photosensitive surface size of photoelectric detector. In Fig. 1, when the laser transmitting power is already certain, the core to effect laser detection performance is laser receiving detection part. Based on the detection principle showed in Fig. 1, this paper researches radiation performance on space target of laser detection receiving system and establishes the photoelectric detection model on space target.

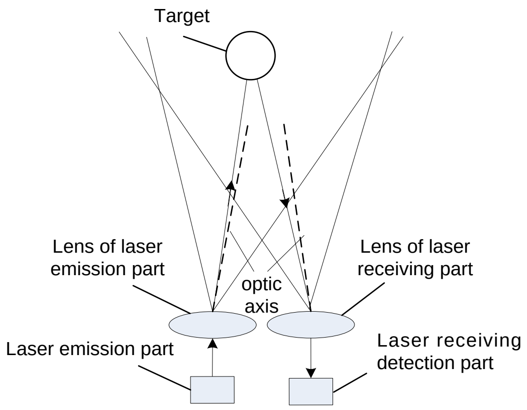


Fig. 1. The detection schematic diagram of laser detection system on space target

In Fig. 1, only when the reflective echo energy is in the effective detection field, the echo energy can be received by photoelectric detector. In order to ensure that the laser energy is strong and the strong laser energy is enough to detect further targets, consequently, the emission angle of laser beam is generally small, and the selected angle range of emitting laser visual field is generally 8-15 degrees. Receiving visual field is generally 3-5 times as much as the emitting laser visual field. When the angle of emission laser is smaller, the reflective echo energy is more concentrated. When the echo energy is stronger, the detection distance is farther.

When the emitting laser field of view and receiving field of view are determined, the influencing factors of the detection performance also include the laser transmitting power, the responsivity of the photoelectric detector and the SNR of the detecting circuit. Under the same conditions to detect, strong laser transmitting power will cause strong reflective echo energy. With certain condition of laser transmitting power, when the responsivity value of detector is high, the value of SNR is high and the detection performance is more excellent.

3. The radiation characteristics of space target in receiving detection area

Based on the detection principle of laser detection system, the receiving energy of laser detection system mainly relies on these parameters which are sky background luminance, reflective radiant energy on target and the aperture size of the optical lens, etc. [12].

Because the space target does not emit light, the radiant energy of target mainly relies on the reflection of sunlight, and it is basically consistent with the sunlight spectra. The target radiance is from the solar radiation, assuming that the solar spectrum illumination is $E(\lambda)$, then, the solar radiation luminous flux received by the space target surface element Δs in the laser detection field is:

$$dF_1 = \int_{\lambda_1}^{\lambda_2} E(\lambda)\cos\alpha\Delta s d\lambda \tag{1}$$

In (1), α is the intersection angle between the sun incident ray and the normal of space target surface element Δs. From Fig. 2, it can be seen that λ_1 and λ_2 are corresponding spectral wavelengths of the photoelectric detector; if $\rho(\lambda)$ is the reflection coefficient of target surface element, the reflective radiation luminous flux of the space target surface element Δs is expressed by formula (2).

$$dF_2 = \int_{\lambda_1}^{\lambda_2} \rho(\lambda)E(\lambda)\cos\alpha\Delta s d\lambda \tag{2}$$

Excepting the effect on the receiving energy of the electrophonic detector from solar spectrum, the receiving energy also is affected by lasing reflection from the surface element of target [13]. Assumed α' is the intersection angle between the laser incident ray and the normal direction of the target surface element Δs, $\rho'(\lambda)$ is laser reflection coefficient of target surface element, $E'(\lambda)$ is reflective luminance on target surface from laser, then the reflective luminous flux on the space target surface element Δs from emitting laser is expressed by formula (3).

$$dF_3 = \int_{\lambda_1}^{\lambda_2} \rho'(\lambda)E'(\lambda)\cos\alpha'\Delta s d\lambda \tag{3}$$

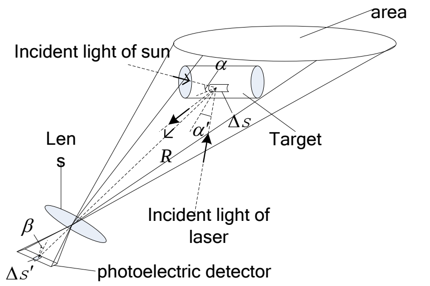


Fig. 2. The space target image principle in photoelectric detection system

The radiation luminous flux received by laser detector is algebraic sum between F_2 and F_3, it can be written as $F= F_2+F_3$.

If the distance between the space target surface element Δs and the detection receiver photosensitive surface element $\Delta s'$ is R, the luminous flux of the photosensitive surface element $\Delta s'$ can be written as formula(4).

$$dF=\frac{\cos\beta}{\pi}\int_{\lambda_1}^{\lambda_2}\frac{1}{R^2}[\rho(\lambda)E(\lambda)\cos\alpha+\rho'(\lambda)E'(\lambda)\cos\alpha']\Delta s\Delta s' d\lambda \tag{4}$$

In (4), β is the angle between the normal direction of photosensitive surface element and the incoming ray of space target radiation luminance. In order to gain the corresponding spectral characteristics' luminance of the unit space target, the surface element integral method is adopted to calculate the total area of space target in the laser detection area, and then the total photosensitive surface luminance of the space target in photoelectric detection receiver can be calculated by formula (5).

$$E=\frac{\cos\beta}{\pi R^2}\int_{\lambda_1}^{\lambda_2}\int_{s}[E_{sun}\rho(\lambda)\cos\alpha+E'(\lambda)\rho'(\lambda)\cos\alpha']\Delta s d\lambda \tag{5}$$

In (5), E_{sun} is the luminance that the sun light reaches laser detection optics system.

4. The photoelectric detection performance of laser detection system

4.1 *SNR* calculation model and analysis in laser detection system

In the laser detection system, SNR is used to weigh photoelectric performance. Assumed S_i is unit photosensitive surface element of the photoelectric detector, dM is signal photoelectron numbers on the photosensitive surface by target radiation; dM can be calculated by formula (6).

$$dM=g_s\cdot A_r\cdot\ell_s\cdot\eta_s\cdot\tau_0\cdot t \tag{6}$$

In (6), g_s is the signal photon stream which is produced from the detector photosensitive surface element S_i, ℓ_s is the filter coefficient of the target signal to the laser detection optical system, η_s is the target signal average quantum efficiency of the photoelectric detector, A_r is the receiving area in detection field of the optical lens, t is the time of the target flying through the laser detection system, and τ_0 is the optical lens transmittance[14].

According to the cross-sectional area of the target function in the detection screen, the total photoelectron number on the photosensitive surface by target radiation can be expressed (7) by.

$$Q=\int_s dMds=\sum_{i=1}^{n}g_s\cdot A_r\cdot\ell_s\cdot\eta_s\cdot\tau_0\cdot t\cdot S_i \tag{7}$$

In (7), n is the total numbers of photosensitive surface element in photoelectric detector.

The corresponding photoelectron number of the background light signal received by photoelectric detector can be expressed as formula (8).

$$B=\sum_{i=1}^{n}g_bA_r\ell_b\eta_b\tau_0t\delta^2(S_b)_i \tag{8}$$

In (8), g_b is the signal photon stream which is produced by the detector photosensitive surface element S_i, δ^2 is unit photosensitive area, ℓ_b is filter factor of the laser detection optical system, η_b is the average quantum efficiency of the photoelectric detector [15], $(S_b)_i$ is a unit area acted by background light on photoelectric detector. Then, the laser detection system's *SNR* can be expressed by formula (9).

$$SNR=\frac{Q}{\sqrt{B}}=\frac{\sum_{i=1}^{n}g_s\cdot\ell_s\cdot\eta_s\cdot\tau_0\cdot t\cdot S_i}{\sqrt{\sum_{i=1}^{n}g_b\cdot\ell_b\cdot\eta_b\cdot\tau_0\cdot t\cdot\delta^2\cdot(S_b)_i/A_r}} \tag{9}$$

According to (9), the functional relation between photoelectron number on photosensitive surface by target radiation and *SNR* can be calculated. When other parameters of laser detection system have been certain, in order to improve the signal-to-noise ratio of laser detection system, it is need to increase the laser reflection area, namely, to increase the corresponding A_r, at the same time, to reduce the influence of background light. Choose optical device with high filter coefficient and photoelectric receiving device with high responsivity to design receiving detection system. When filter coefficient is high, the received effective laser echo energy was stronger. At the same time, the use of high responsivity detector can effectively receive echo energy of moving target with high speed. In addition, when the detection circuit is designed, it is possible to reduce the inherent noise signal, so that the signal-to-noise ratio of detection system can be effectively improved.

For laser detection system in sea level, if the value of *SNR* of the laser detection system is larger than 5.6, the detection performance of the laser detection system will be the best.

4.2 The detection distance calculation model of laser detection system

According to the photoelectric detection principle on space target in sea level and based on the definition of contrast modulation, contrast *C* can be expressed as.

$$C = \frac{E_{\max} - E_{\min}}{E_{\max} + E_{\min}} = \frac{E_t}{E_t + 2(E_b + E_0)} \tag{10}$$

In (10), E_t is the irradiance of space target on the detector photosensitive surface, which can be calculated according to formula (5) and Planck's law, E_b stands for the irradiance of background light on the detector photosensitive surface, E_0 stands for the irradiance of the detector photosensitive surface from detecting imaging lens [16].

$$E_t = \frac{\tau_0 \tau_1}{4} M(\lambda) \cdot \left| \frac{D}{f} \right|^2 \tag{11}$$

$$E_b = \frac{\tau_0 \tau_1}{4} \cdot L_b \cdot \left| \frac{D}{f} \right|^2 \tag{12}$$

$$E_0 = \frac{1}{4} \cdot M \cdot \left| \frac{D}{f} \right|^2 \tag{13}$$

In (11), (12), (13), $M = \tau_0 \cdot M(\lambda)$, τ_0 is the optical lens transmittance, τ_1 is the atmosphere transmittance, L_b is background luminance. The formula (9) can be transferred into (14).

$$C = \frac{M(\lambda)\tau_0\tau_1}{M(\lambda)\tau_0\tau_1 + 2(\tau_0 \cdot \tau_1 \cdot L_b + M)} \tag{14}$$

Here, $M(\lambda)$ can be calculated by using Planck's law.

The detection distance of laser detection system was designated as *R*, its expression is shown as (15).

$$R = f \cdot \sqrt{\frac{M(\lambda) \cdot \tau_1 \cdot \tau_0}{2(M + \pi\tau_0 L_b)} \left| \frac{A_f}{A_t} \right| \cdot \left| \frac{1-C}{C} \right|} \tag{15}$$

In (15), A_t is the imaging area of target on the detector photosensitive surface in space detection coverage. A_f is reflective area of target.

Based on formula (15), when the value of the background luminance is bigger, the contrast of the laser echoes is smaller, which is not conducive to improve the detection distance. In order to improve the detection distance of laser detection system, laser detection system should work under the appropriate background luminance conditions. If the background luminance is strong, the effective laser echo energy of target will weaken, detection distance will reduce. When the background luminance is weak, the difference between the reflective laser echo energy from target and the energy from background light will become large, which is conducive to improve the detection distance. In conclusion, based on these parameters such as background illumination, radiance of target, modulation contrast etc., detection distance of laser detection system can be figured out effectively.

5. Calculation and experiment analysis

5.1 Calculation analysis the influence of background illumination to the laser detection performance

According to the calculation principle mentioned above, the emission peak power of lasing is 60W, the laser impulse frequency is 850Hz, the lens focal distance is 24mm, receiving lens's transmission efficiency is 0.75, the photosensitive surface area of photoelectric detection receiver is $4mm \times 4mm$, and the conversion response rate of the photoelectric detector is (3-8) $\times 10^{-6} \mu s$.

Based on the *SNR*'s formula of the laser detection system, the detection *SNR* change curve of the photoelectric detection system in different sky background luminance can be obtained under the condition of the unchanged solar altitude angle in the laser detection area. Fig. 3 shows the change curves of *SNR* under different sky background luminance.

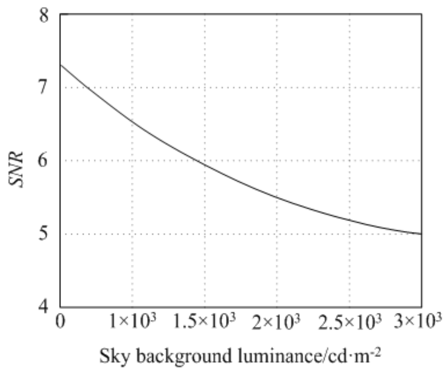


Fig. 3. The change curves of SNR under different sky background luminance

It is known from Fig. 3 that the value of *SNR* decreases with the increasing of background luminance, when the design parameters of laser optical detection system are unchanged. The value of *SNR* is less than 5.6 when the value of background luminance is greater than $2.5 \times 10^3 cd/m^2$, which is lower than the steady working requirement of laser detection system. It means that when the value of background luminance is greater than $2.5 \times 10^3 cd/m^2$, the output signal of photoelectric detector reaches saturation state, and the laser detection system cannot detect and recognize the space targets.

Fig. 4 shows the detection capability curve of different caliber targets under different background illumination conditions. From Fig. 4, it shows that for the same caliber target, with the increasing of the background luminance, the *SNR* and the detection performance decreases, which is not conducive to detect targets. When the target caliber increases, the detection ability of space target will improve. The improving reason of detection ability is that the radiating area of space target in laser detection filed increases. The energy obtained by the electrophonic detector increases, the number of output photon stream also increases, which results in the growth of detection output signal. When the background luminance is $1.5{\times}10^3 cd/m^2$ and the target diameter is 600*mm*, the detection output signal reaches 5*V*. When the background luminance is less than $1.5{\times}10^3 cd/m^2$, detection performance doesn't decline obviously, because laser detection system uses infrared detection technology, which can lead to the signal-to-noise ratio has little changes in low background luminance; But when the background luminance is higher than $4.0{\times}10^3 cd/m^2$, the background luminance will act on the target, which will decay the target reflection contrast obviously, so under the condition that background luminance is more than $4.0{\times}10^3 cd/m^2$, the signal-to-noise ratio of detection system will be reduced and detection performance will decline. These changes will be not conducive to the detection. In order to improve the detection performance of the system, the band pass filter is adopted to eliminate the effect from strong background illumination.

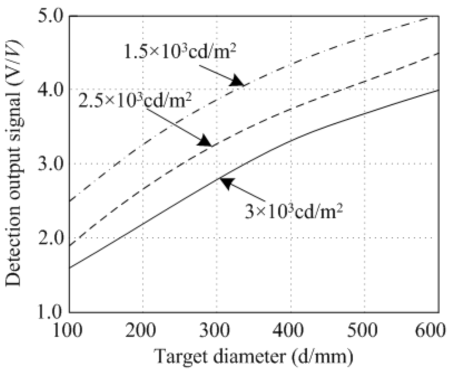


Fig. 4. The changing curve of detection output signal and target diameter under different background luminance

5.2 Calculation analysis the influence of optical lens spectral filtering to the laser detection performance

For laser detection system in sea level, because the space target and background luminance are a changing process of the spatial and temporal. It can be known, according to the calculation model of target luminance and sky background luminance, that the laser detection performance is also related to the spectral filtering parameter of optical lens when the detection system design parameters are known. The laser detection performance is affected by background signal's filter coefficient and the target signal's filter coefficient in different filtering methods. The normalized photon flux curve of sky background light is given. As the background luminance and the target luminance are unchanged, Table 1 shows the change of *SNR* when cut-off wavelength varies from 0.9~1.3 um.

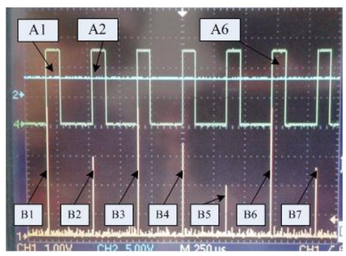
Table 1. SNR and cut-off wavelength

cut-off wavelength/um	0.9	1.0	1.1	1.2	1.3
improving ratio of SNR	2.18	1.92	1.66	1.54	1.32

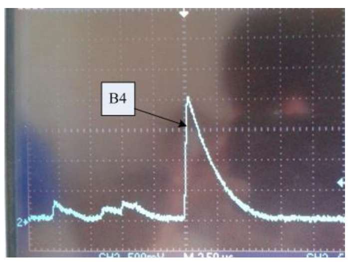
It can be known from Table 1, the spectral filtering method can effectively improve the laser detection performance of laser detection system, which can reduce the influence degree on detection receiving system from environment stray light.

5.3 The experiment and analysis on detection performance of laser detection system

In order to verify the detection performance model of laser detection system in sea level, through the dynamic test for different targets at different distances and sizes, output signals of dynamic target is acquired. When the cylindrical target diameter is 200mm, length is 80mm, the luminance is $2.0{\times}10^3 cd/m^2$ and the detection distance is 8.5 meters, and the target crosses the laser detection field with the speed of 340*m/s*, the acquired oscillogram of output signals are shown in Fig. 5.



(a)



(b)

Fig. 5. The gathering output signals by using oscilloscope

Fig. 5 shows gathering output signals by using oscilloscope, *A* is emitted laser impulse; *B* is receiving energy of detector. Under the laser impulse emitting continuously, it can be seen from Fig. 5 (a), when the target crosses the laser detection field, because of the changes of detection distance, the output signals are not same at different time. Accompanied by the decrease of detection distance, the output signals will increase. Fig. 5 (b) shows amplified output signal *B4*, it indicates that the peak value of the output signal reaches 2100mV.

The data in Table 2 are the peak value of the output signals in detection field of different targets, when the background luminance is $2.0\times10^3 cd/m^2$ and the detection distance is 10.5m. Table 2 shows, with the increase of target size, the output signals become strong at the same detection distance, but the inherent noise nearly does not change. Which illustrates the target size can bring obvious change to receiving energy of detector in laser detection system.

Table 2. The output signals in different sizes of target when background luminance is $2.0\times10^3 cd/m^2$

Num	The size of target	Output signal with target (V/mV)	Inherent noise (V/mV)
1	100mm×60mm	1963	508
2	120mm×100mm	2168	517
3	200mm×100mm	2485	543
4	200mm×150mm	3254	598
5	250mm×150mm	3471	585

Table 3 is gather the output signal in laser detection field under the same size of target when the background luminance is $4.0\times10^3 cd/m^2$ and the detection distance is 10.5m. It can be seen from Table 3, with the increase in background luminance, the inherent noise ascends, but the peak value of the output signal does not change obviously. It is clear that the inherent noise of detector becomes larger as the background luminance increases, which is not beneficial to detect. In order to eliminate the effect of strong background luminance, the spectral filter is added in the receiving optics lens. This laser detection system has selected a filter whose filter factor is 0.68. Due to the difference of background spectral characteristics, when the parameters of the photoelectric detection system are certain, the appropriate spectral filtering method is chosen according to the characteristics of the different background luminance spectrum. Table 4 shows the improved testing results by using appropriate spectral filtering technology.

Table 3. The output signals in different sizes of target when background luminance is $4.0\times10^3 cd/m^2$

Num	The size of target	Output signal with target (V/mV)	Inherent noise (V/mV)
1	100mm×60mm	1982	1129
2	120mm×100mm	2431	1154
3	200mm×100mm	3123	1081
4	200mm×150mm	3658	1143
5	250mm×150mm	3681	1098

Table 4. The output signals in different sizes of target by using appropriate spectral filtering technology

Num	The size of target	Output signal with target (V/mV)	Inherent noise (V/mV)
1	100mm×60mm	2065	663
2	120mm×100mm	2118	701
3	200mm×100mm	3245	674
4	200mm×150mm	3476	659
5	250mm×150mm	3347	715

Table 4 shows that the spectral filtering technology could minimize the background radiation photons and inhibit the saturation of detector, at the same time, the target signals could decay as little as possible and the *SNR* and contrast ratio could be improved. Therefore, the laser detection performance could be improved effectively.

6. Conclusions

According to detection principle of laser detection system, this paper analyzes the detection performance and the influencing factors of the laser detection system, establishes the theoretical model of detection performance of laser receiving detection system and the SNR calculation model of the laser detection system, and gives the formula of detection distance. The results of calculation and analysis show that the laser detection performance is closely related to the space targets characteristics and photoelectric detection characteristics. The results of calculation and experiment also show that the laser detection performance is mainly affected by strong background light. Adopting appropriate spectral filtering technology to weaken the influence of background luminance and inhibit the saturation of the detector, at the same time, target signal changes little, which improves the *SNR* and contrast ratio of detection system. It enhances detection performance of laser detection system under strong background light conditions. Theoretical models and the calculation method in this paper provide a reliable basis for improving design of laser detection system under different circumstances, and effectively improve detection performance of shipboard general purpose photo-sensor in sea surface.

References

[1] Q. H. Liu, W. F. Shi, B. X. Yan, etc. Acta Photonica Sinica, **33**(11), 1409 (2001).
[2] Zhang Jihua, Fan Ruyu, Zhao Ning, Infrared and laser engineering, **43**(1), 212 (2014).
[3] Hanshan Li, Zhiyong Lei, IEEE sensors journal, **13**(5), 1959 (2013).
[4] S. H. Abadi, D. Rouseff, D. R. Dowling, J. Acoustic. Soc. Am., **131**(4), 2599 (2012).
[5] E. Huseynov, N. Isnailov, S. R. Samedov, International Journal of infrared and millimeter waves, **23**(9), 1337 (2000).

[6] J. Bjorkman, D. Baroudi, R. Latva, Fire safety journal, **37**(4), 395 (2002).
[7] Y. X. Liu, Y. Ghanu, R. Xionu, Acta Photonica Sinica, **25**, (6), 550 (1996).
[8] Hanshan Li, Zhiyong Lei, Sensor review, **33**(4), 315 (2013).
[9] N. Jinping, H. Tian, Optical Technique, **14**(1), 34 (2008).
[10] Li Hanshan, Optoelectron. Adv. Mat., **8**(7-8), 653 (2014).
[11] Li Qi-hu, Li Min, Yang Xiu-ting, Acta Acustica, **33**(4), 290 (2008).
[12] Li Bincheng, Optic electronic engineering, **6**(2), 21 (1989).
[13] Hanshan Li, Yanran Li, Sensors & Transducers, **164**(2), 249 (2014).
[14] B. Wenzhuo, C. Mingyu, Z. Wei. Et al. Acta optica sinica, **30**, 2249 (2012).
[15] Wan Min, Su Yi, Yang Rui, High power laser and particle beams, **15**(12), 1151 (2003).
[16] Zhang Jihua, Yaodongsheng, Tan Bin, Acta optica sinica, **28**(6), 1178 (2008).

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